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3-Phase ACIM Volt per Hertz Control Using 56F80x

Designer Reference Manual

56800 Hybrid Controller

DRM021/D
Rev. 0, 03/2003

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3-Phase ACIM V/Hz Control Using 56F80x

Designer Reference Manual — Rev 0

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Revision history

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The following revision history table summarizes changes contained in this document. For your convenience, the page number designators have been linked to the appropriate location.

Revision history

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Section 1. Introduction

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1.2 Introduction

This section describes the design of a 3-phase AC induction motor drive with volt per hertz control in closed loop (hereinafter called V/Hz OL). It is based on Motorola's 56F80x digital signal processor (DSP), which is dedicated for motor control applications. The system is designed as a motor control system for driving medium power, 3-phase AC induction motors. The part is targeted toward applications in both industrial and home appliance industries, such as washing machines, compressors, air conditioning units, pumps, or simple industrial drives. The software design takes advantage of Quick_Start developed by Motorola.

The drive introduced here is intended as an example of a 3-phase AC induction motor drive. The drive serves as an example of AC V/Hz motor control system design using Motorola DSP.

This document includes the basic motor theory, system design concept, hardware implementation, and software design, including the PC Master visualization tool inclusion.

1.3 Motorola DSP Advantages and Features

The Motorola DSP56F805 is well suited for digital motor control, combining the DSP's calculation capability with MCUs controller features on a single chip. This DSP offers a rich dedicated peripherals

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set, such as pulse width modulation (PWM) modules, analog-to-digital converter (ADC), timers, communication peripherals (SCI, SPI, CAN), on-board flash and RAM.

The DSP56F805, provides the following peripheral blocks:

- Two pulse width modulator modules (PWMA & PWMB), each with six PWM outputs, three current status inputs, and four fault inputs, fault tolerant design with deadtime insertion, supports both center- and edge- aligned modes
- Two 12-bit, analog-to-digital convertors (ADCs), supporting two simultaneous conversions with dual 4-pin multiplexed inputs, ADC and can be synchronized by PWM modules synchronized
- Two quadrature decoders (Quad Dec0 & Quad Dec1), each with four inputs, or two additional quad timers A & B
- Two dedicated general purpose quad timers totalling 6 pins: Timer C with 2 pins and Timer D with 4 pins
- CAN 2.0 A/B module with 2-pin ports used to transmit and receive
- Two serial communication interfaces (SCI0 & SCI1), each with two pins, or four additional MPIO lines
- Serial peripheral interface (SPI), with configurable 4-pin port, or four additional MPIO lines
- Computer operating properly (COP) timer
- Two dedicated external interrupt pins
- Fourteen dedicated multiple purpose I/O (MPIO) pins and 18 multiplexed MPIO pins
- External reset pin for hardware reset
- JTAG/on-chip emulation (OnCE™)
- Software-programmable, phase lock loop-based frequency synthesizer for the DSP core clock
- Memory configuration
  - 32252 × 16-bit words of program flash
  - 512 × 16-bit words of program RAM

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- 2K × 16-bit words of data RAM
- 4K × 16-bit words of data flash
- 2K × 16-bit words of boot flash

The pulse-width-modulation (PWM) block offers high freedom in its configuration enabling to control the AC induction motor in efficient way.

The PWM block has the following features:

- Three complementary PWM signal pairs, or six independent PWM signals
- Features of complementary channel operation
- Deadtime insertion
- Separate top and bottom pulse width correction via current status inputs or software
- Separate top and bottom polarity control
- Edge-aligned or center-aligned PWM reference signals
- 15-bits of resolution
- Half-cycle reload capability
- Integral reload rates from one to 16
- Individual software-controlled PWM output
- Programmable fault protection
- Polarity control
- 20-mA current sink capability on PWM pins
- Write-protectable registers

The PWM outputs are configured in the complementary mode in this application.

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Section 2. Control Theory

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2.2 Target Motor Theory

The AC induction motor is a workhorse of an adjustable speed drive systems. The most popular type is the 3-phase, squirrel-cage AC induction motor. It is maintenance-free, lower noise and efficient motor. The stator is supplied by a balanced 3-phase AC power source.

The synchronous speed n_s of the motor is given by

$$n_s = \frac{120 \times f_s}{p} \qquad [rpm] \tag{2-1}$$

where f_s is the synchronous stator frequency in Hz, and p is the number of stator poles. The load torque is produced by slip frequency. The motor speed is characterized by a slip s_r:

$$s_r = \frac{(n_s - n_r)}{n_s} = \frac{n_{sl}}{n_s} \qquad [-] \tag{2-2}$$

where n_r is the rotor mechanical speed and n_{sl} is the slip speed, both in rpm. **Figure 2-1** illustrates the torque characteristics and corresponding slip. As it can be seen from Equation 2-1 and Equation 2-2 the motor speed is controlled by variation of a stator frequency with influence of the load torque.

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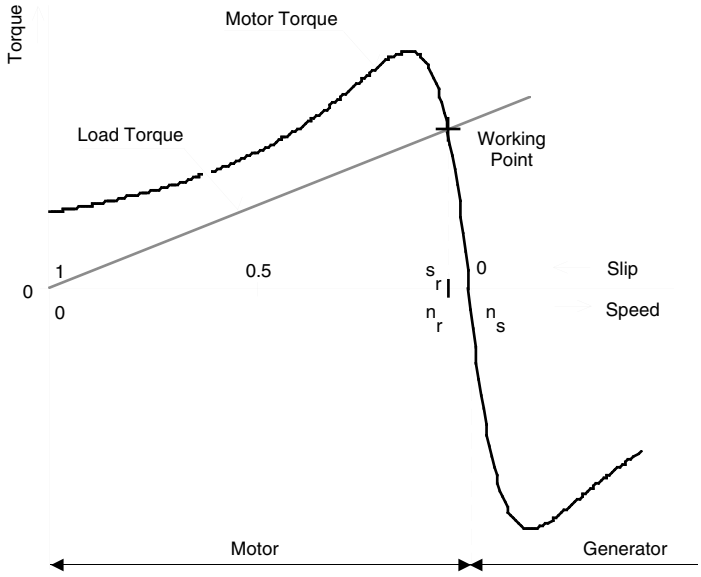

Figure 2-1. Torque-Speed Characteristic at Const. Voltage & Frequency

In adjustable speed applications the AC motors are powered by inverters. The inverter converts DC power to AC power at required frequency and amplitude. The typical 3-phase inverter is illustrated in **Figure 2-2**.

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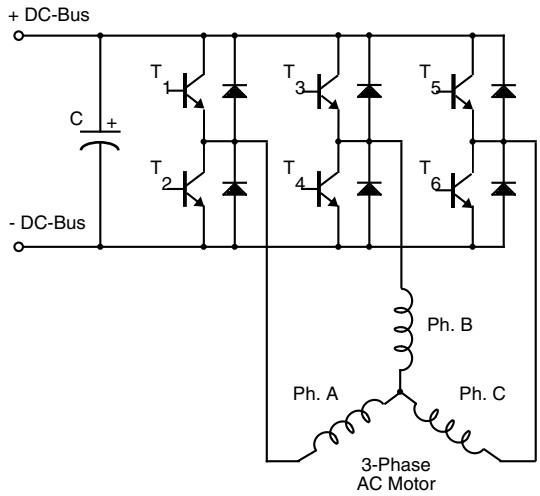

Figure 2-2. 3- Phase Inverter

The inverter consists of three half-bridge units where the upper and lower switch is controlled complementarily - meaning when the upper one is turned-on, the lower one must be turned-off and vice versa. As the power device's turn-off time is longer than its turn-on time, some dead-time must be inserted between the turn-off of one transistor of the half-bridge and turn-on of it's complementary device. The output voltage is mostly created by a pulse width modulation (PWM) technique where an isosceles triangle carrier wave is compared with a fundamental-frequency sine modulating wave, and the natural points of intersection determine the switching points of the power devices of a half bridge inverter. This technique is shown in **Figure 2-3.** The 3-phase voltage waves are shifted 120^{o} to each other and thus a 3-phase motor can be supplied.

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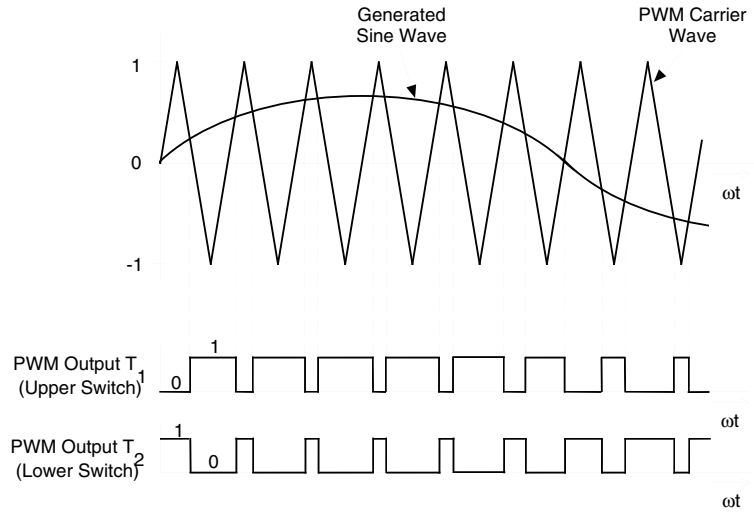

Figure 2-3. Pulse Width Modulation

The most popular power devices for motor control applications are Power MOSFETs and IGBTs.

A Power MOSFET is a voltage controlled transistor. It is designed for high frequency operation and it has a low voltage drop, thus it has low power losses. However, the saturation temperature sensitivity limits the MOSFET application in high power applications.

An insulated gate bipolar transistor (IGBT) is a bipolar transistor controlled by a MOSFET on its base. The IGBT requires low drive current, has fast switching time, and is suitable for high switching frequencies. The disadvantage is its higher voltage drop of the bipolar transistor, causing higher conduction losses.

2.3 Volt per Hertz Control

Volt per Hertz control methods is the most popular method of Scalar Control, controls the magnitude of the variable like frequency, voltage or

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current. The command and feedback signals are DC quantities, and are proportional to the respective variables.

The purpose of the volt per hertz control scheme is to maintain the air-gap flux of AC Induction motor in constant in order to achieve higher run-time efficiency. In steady state operation the machine air-gap flux is approximately related to the ratio V_s/f_s, where V_s is the amplitude of motor phase voltage and f_s is the synchronous electrical frequency applied to the motor. The control system is illustrated in **Figure 2-4.** The characteristic is defined by the base point of the motor. Below the base point the motor operates at optimum excitation because of the constant V_s/f_s ratio. Above this point the motor operates under-excited because of the DC-Bus voltage limit.

A simple close-loop volts/hertz speed control for an induction motor is the control technique targeted for low performance drives. This basic scheme is unsatisfactory for more demanding applications where speed precision is required.

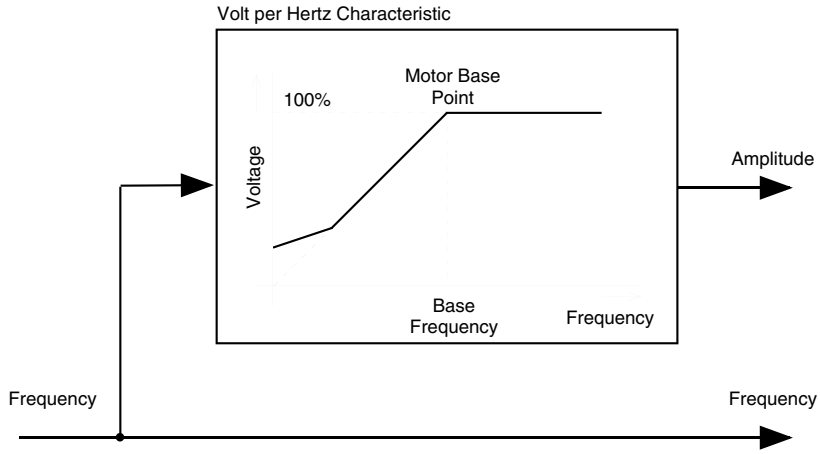

Figure 2-4. Volts per Hertz Control Method

2.4 Speed Close Loop System

To improve the system performance, a closed-loop volts per hertz control was introduced. In this method a speed sensor measures the actual motor speed and the system takes this input into consideration. A

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number of applications use the closed-loop volts per hertz method because of its simple and relatively good speed accuracy, but it is not suitable for systems requiring servo performance or excellent response to highly dynamic torque/speed variations.

Figure 2-5 illustrates the general principle of the speed PI control loop.

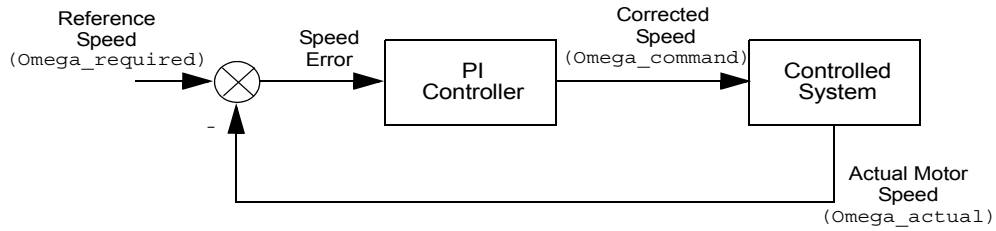

Figure 2-5. Closed Loop Control System

The speed closed loop control is characterized by the measurement of the actual motor speed. This information is compared with the reference speed while the error signal is generated. The magnitude and polarity of the error signal correspond to the difference between the actual and required speed. Based on the speed error the PI controller generates the corrected motor stator frequency in order to compensate for the error.

In a case of AC V/Hz closed loop application, the feedback speed signal is derived from incremental encoder using the quadrature decoder. The speed controller constants have been tuned experimentally according to the actual load.

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Section 3. System Concept

3.1 System Design Concept

The system is designed to drive a 3-phase AC induction motor. The application meets the following performance specifications:

- Targeted for DSP56F80XEVM platforms
- Running on 3-phase ACIM motor control development platform at variable line voltage 115 - 230V AC
- Control technique incorporates
  - motoring and generating mode
  - bi-directional rotation
  - V/Hz speed close loop
- Manual Interface (Start/Stop switch, Up/Down push button speed control, LED indication)
- PC Master Interface (motor start/stop, speed set-up)
- Power stage identification
- Overvoltage, undervoltage, overcurrent, and overheating fault protection

The introduced AC drive is designed as a DSP system that meets the following general performance requirements:

Table 3-1. Motor / Drive Specifications

Motor Characteristics:	**Motor Type**	4 poles, three phase, star connected, squirrel cage AC motor (standard industrial motor)
	Speed Range:	< 5000 rpm
	Base Electrical Frequency:	50 Hz
	Max. Electrical Power:	180 W
	Delta Voltage (rms):	200V (Star)

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System Concept

Drive Characteristics:	**Transducers:**	IRC -1024 pulses per rev.
	Speed Range	<2250 rpm @ 230 V <1200 rpm @ 115 V
	Line Input:	230V / 50Hz AC 115V / 60Hz AC
	Max. DC Bus Voltage	400 V
	Control Algorithm	Close Loop Control
	Optoisolation	Required
Load Characteristic:	**Type**	Varying

The DSP runs the main control algorithm. According to the user interface input and feedback signals, it generates 3-phase PWM output signals for the motor inverter.

A standard system concept is chosen for the drive, and illustrated in **Figure 3-1.** The system incorporates the following hardware boards:

- Power supply rectifier
- 3-phase inverter
- Feedback sensors: speed, DC-bus voltage, DC-bus current, temperature
- Optoisolation
- Evaluation board DSP56F805

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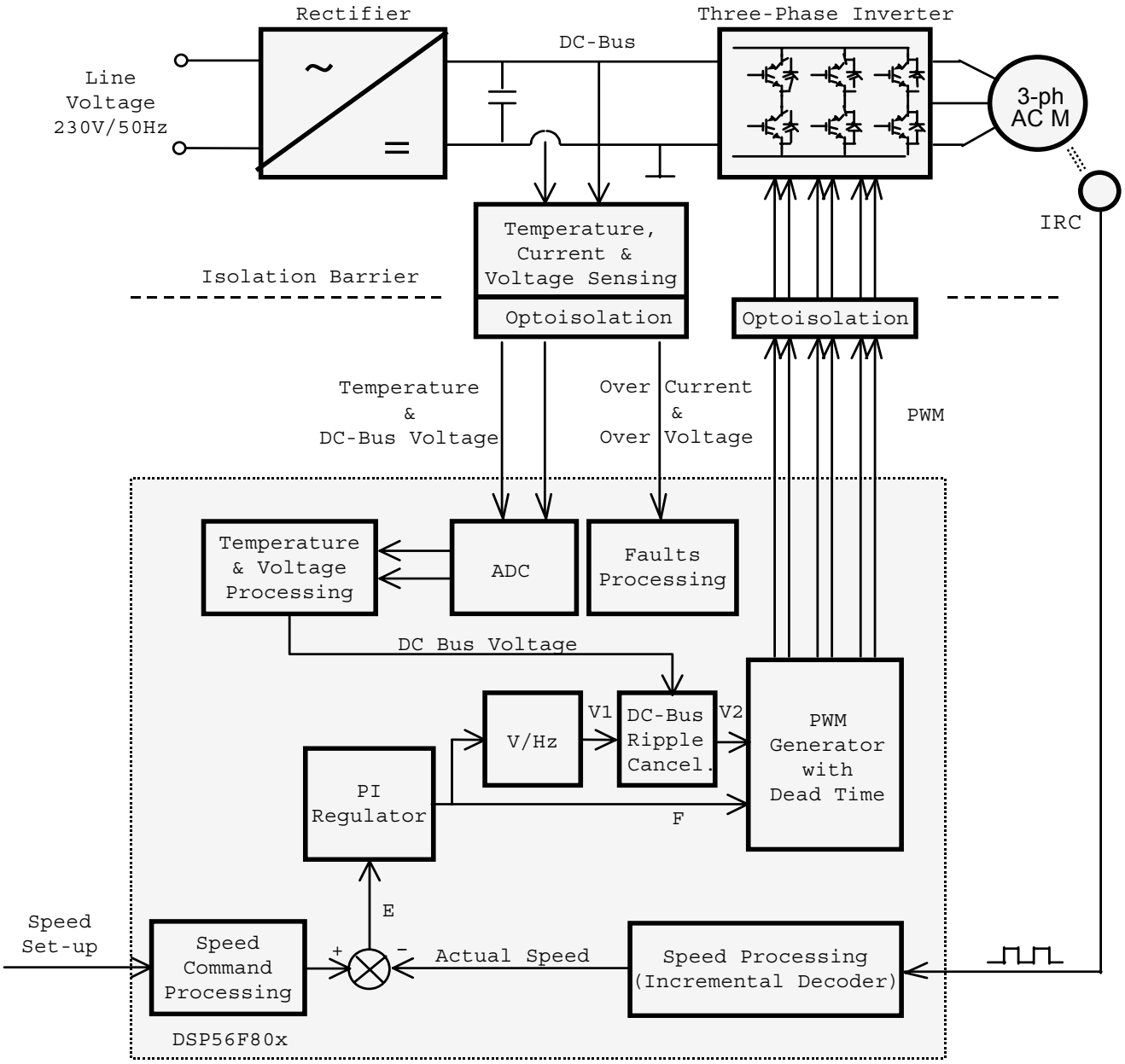

Figure 3-1. System Concept

The Control Process:

When the start command is accepted, using the Start/Stop switch, the state of the inputs is periodically scanned. According to the state of the

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control signals (Start/Stop switch, speed up/down buttons or PC Master set speed) the speed command is calculated using an acceleration/deceleration ramp.

The comparison between the actual speed command and the measured speed generates a speed error E. The speed error is brought to the speed PI controller that generates a new corrected motor stator frequency. With the use of the V/Hz ramp the corresponding voltage is calculated and then DC-bus ripple cancellation function eliminates the influence of the DC-bus voltage ripples to the generated phase voltage amplitude. The PWM generation process calculates a 3-phase voltage system at the required amplitude and frequency, includes dead time. Finally the 3-phase PWM motor control signals are generated.

The DC-bus voltage and power stage temperature are measured during the control process. They are overvoltage, undervoltage, and overheating protection of the drive. Both undervoltage protection and overheating are performed by ADC and software while the DC-bus overcurrent and overvoltage fault signals are connected to PWM fault inputs.

If any of the above mentioned faults occurs, the motor control PWM outputs are disabled in order to protect the drive and the fault state of the system is displayed in PC Master control page.

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4.2 Introduction

The motor control system is designed to drive the 3-phase AC motor in a speed close loop.

The designed software is capable to run only on high voltage HW set described below.

Other power module boardswill be denied due to board identification build in SW. This feature protects misuse of the HW module.

4.3 The High Voltage Hardware Set

The system configuration is shown in **Figure 4-1.**

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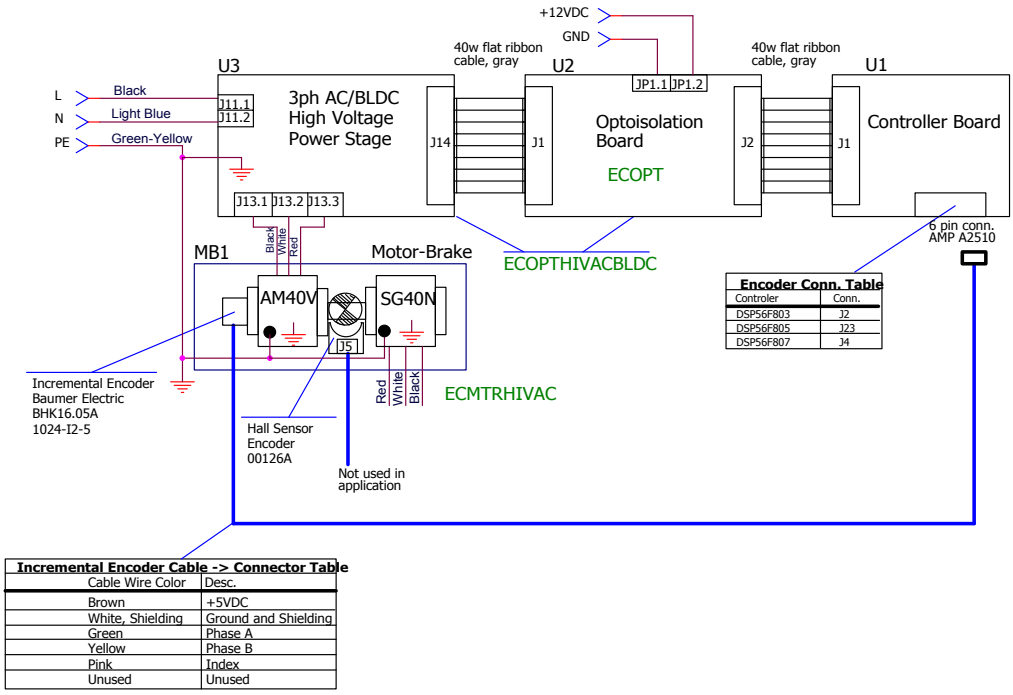

Incremental Encoder Cable -> Connector Table

Cable Wire Color	Desc.
Brown	+5VDC
White, Shielding	Ground and Shielding
Green	Phase A
Yellow	Phase B
Pink	Index
Unused	Unused

Figure 4-1. High Voltage HW System Configuration

All the system parts are supplied and documented according to the following references:

- U1 - Controller board for DSP56F805:
  - supplied as: DSP56805EVM
  - described in: *DSP56F805EVMUM/D DSP Evaluation Module Hardware User's Manual*
- U2 - 3-ph AC/BLDC high voltage power stage
  - supplied in kit with optoisolation board as: ECOPTHIVACBLDC
  - described in: *MEMC3BLDCPSUM/D - 3 Phase Brushless DC High Voltage Power Stage*
- U3 - Optoisolation board
  - supplied with 3-ph AC/BLDC high voltage power stage as: ECOPTHIVACBLDC

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  - or supplied alone as: ECOPT - optoisolation board
  - described in: *MEMCOBUM/D Optoisolation board User's Manual*
- MB1 motor-brake AM40V + SG40N
  - supplied as: ECMTRHIVAC

WARNING: ***It is strongly recommended to use an opto-isolation (optocouplers and optoisolation amplifiers) during the development time to avoid any damage to the development equipment.***

NOTE: *The detailed description of individual boards can be found in comprehensive users' manuals belonging to each board. The user manual incorporates the schematic of the board, description of individual function blocks and bill of materials. Individual boards can be ordered from Motorola as a standard product from http://mot-sps.com/motor/devtools/index.html.*

This section describes the design of the software blocks of the drive. The software will be described in terms of data flow and state diagrams.

4.4 DSP56F805EVM Control Board

The DSP56F805EVM facilitates the evaluation of various features present in the DSP56F805 part. The DSP56F805EVM can be used to develop real-time software and hardware products based on the DSP56F805. The DSP56F805EVM provides the features necessary for a user to write and debug software, demonstrate the functionality of that software and interface with the customer's application-specific device(s). The DSP56F805EVM is flexible enough to allow a user to fully exploit the DSP56F805's features to optimize the performance of their product, as shown in **Figure 4-2**.

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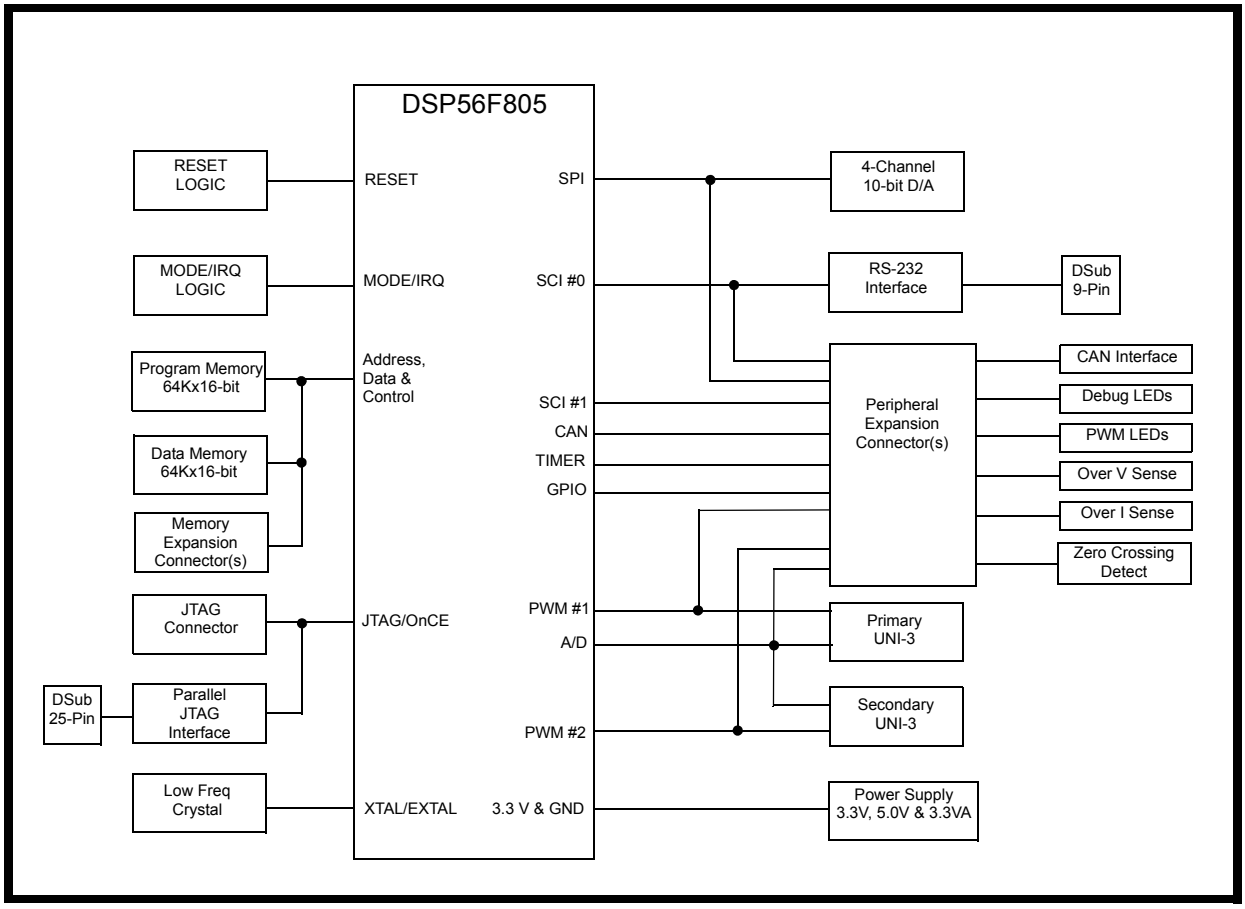

Figure 4-2. Block Diagram of the DSP56F805EVM

4.4.1 DSP56F805EVM Configuration Jumpers

Eighteen jumper groups, (JG1-JG18), shown in **Figure 4-3**, are used to configure various features on the DSP56F805EVM board. **Table 4-1** describes the default jumper group settings.

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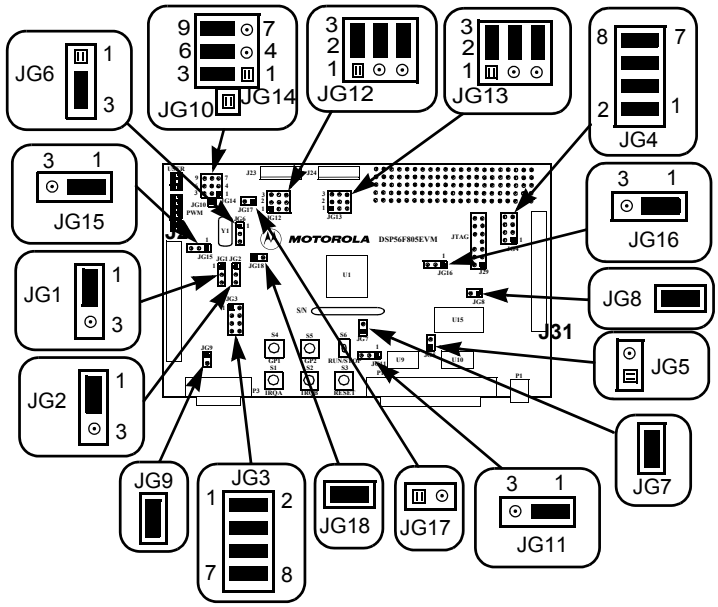

Figure 4-3. DSP56F805EVM Jumper Reference

Table 4-1. DSP56F805EVM Default Jumper Options

Jumper Group	Comment	Jumpers Connections
JG1	PD0 input selected as a high	1–2
JG2	PD1 input selected as a high	1–2
JG3	Primary UNI-3 serial selected	1–2, 3–4, 5–6 & 7–8
JG4	Secondary UNI-3 serial selected	1–2, 3–4, 5–6 & 7–8
JG5	Enable on-board Parallel JTAG Host Target Interface	NC
JG6	Use on-board crystal for DSP oscillator input	2–3
JG7	Selects DSP's Mode 0 operation upon exit from reset	1-2
JG8	Enable on-board SRAM	1–2
JG9	Enable RS-232 output	1–2
JG10	Secondary UNI-3 Analog Temperature Input unused	1–2
JG11	Use Host power for Host Target Interface	1–2

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Table 4-1. DSP56F805EVM Default Jumper Options (Continued)

Jumper Group	Comment	Jumpers Connections
JG12	Primary Encoder Input Selected	2–3, 5–6 & 8–9
JG13	Secondary Encoder Input Selected	2–3, 5–6 & 8–9
JG14	Primary UNI-3 3-Phase Current Sense Selected as Analog Inputs	2–3, 5–6 & 8–9
JG15	Primary UNI-3 Phase A Over-Current Selected for FAULTA1	1–2
JG16	Secondary UNI-3 Phase B Over-Current Selected for FAULTB1	1–2
JG17	CAN termination unselected	NC
JG18	Use on-board crystal for DSP oscillator input	1–2

An interconnection diagram is shown in Figure 4-4 for connecting the PC and the external 12V DC power supply to the DSP56F805EVM board.

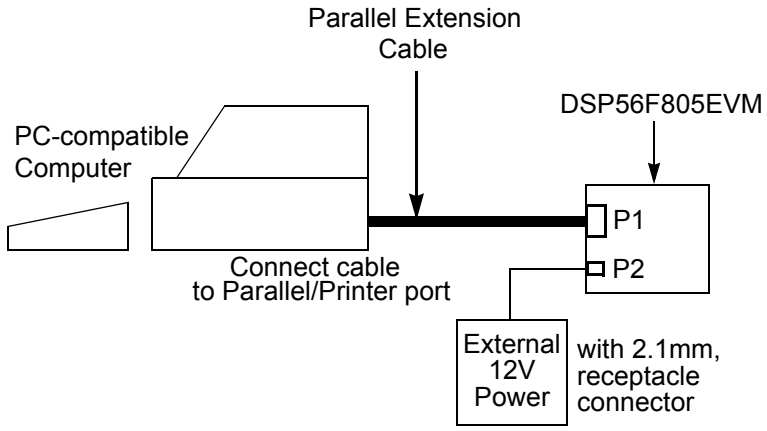

Figure 4-4. Connecting the DSP56F805EVM Cables

Perform the following steps to connect the DSP56F805EVM cables:

1. Connect the parallel extension cable to the Parallel port of the host computer.
2. Connect the other end of the parallel extension cable to P1, shown in Figure 4-4, on the DSP56F805EVM board. This provides the connection which allows the host computer to control the board.

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3. Make sure that the external 12V DC, 4.0A power supply is not plugged into a 120V AC power source.
4. Connect the 2.1mm output power plug from the external power supply into P2, shown in **Figure 4-4**, on the DSP56F805EVM board.

Apply power to the external power supply. The green Power-On LED, LED10, will illuminate when power is correctly applied.

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4.5 3-Phase AC BLDC High Voltage Power Stage

Motorola's embedded motion control series high-voltage (HV) ac power stage is a 180-watt (one-fourth horsepower), 3-phase power stage that will operate off of dc input voltages from 140 to 230 volts and ac line voltages from 100 to 240 volts. In combination with one of the embedded motion control series control boards and an optoisolation board, it provides a software development platform that allows algorithms to be written and tested without the need to design and build a power stage. It supports a wide variety of algorithms for both ac induction and brushless dc (BLDC) motors.

Input connections are made via 40-pin ribbon cable connector J14. Power connections to the motor are made on output connector J13. Phase A, phase B, and phase C are labeled PH_A, Ph_B, and Ph_C on the board. Power requirements are met with a single external 140- to 230-volt dc power supply or an ac line voltage. Either input is supplied through connector J11. Current measuring circuitry is set up for 2.93 amps full scale. Both bus and phase leg currents are measured. A cycle-by-cycle over-current trip point is set at 2.69 amps.

The high-voltage ac power stage has both a printed circuit board and a power substrate. The printed circuit board contains IGBT gate drive circuits, analog signal conditioning, low-voltage power supplies, power factor control circuitry, and some of the large, passive, power components. All of the power electronics which need to dissipate heat are mounted on the power substrate. This substrate includes the power IGBTs, brake resistors, current sensing resistors, a power factor correction MOSFET, and temperature sensing diodes. **Figure 4-5** shows a block diagram.

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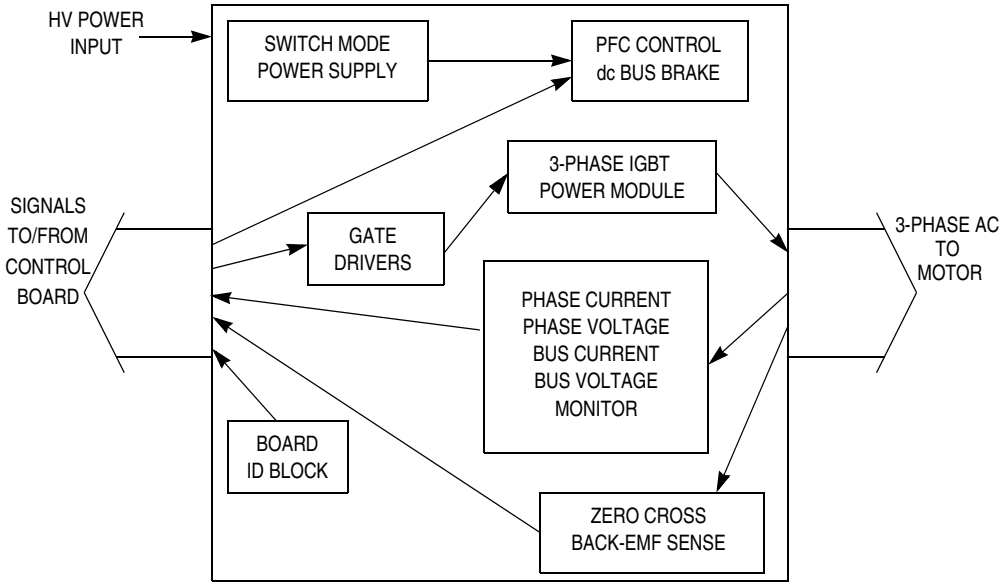
HV POWER INPUT
SWITCH MODE POWER SUPPLY
PFC CONTROL dc BUS BRAKE
3-PHASE IGBT POWER MODULE
SIGNALS TO/FROM CONTROL BOARD
GATE DRIVERS
3-PHASE AC TO MOTOR
PHASE CURRENT PHASE VOLTAGE BUS CURRENT BUS VOLTAGE MONITOR
BOARD ID BLOCK
ZERO CROSS BACK-EMF SENSE

Figure 4-5. 3-Phase AC High Voltage Power Stage

The electrical characteristics in **Table 4-2** apply to operation at 25°C with a 160-Vdc power supply voltage.

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Table 4-2. Electrical Characteristics of Power Stage

Characteristic	Symbol	Min	Typ	Max	Units
dc input voltage	Vdc	140	160	230	V
ac input voltage	Vac	100	208	240	V
Quiescent current	I_{CC}	—	70	—	mA
Min logic 1 input voltage	V_{IH}	2.0	—	—	V
Max logic 0 input voltage	V_{IL}	—	—	0.8	V
Input resistance	R_{In}	—	10 kΩ	—	
Analog output range	V_{Out}	0	—	3.3	V
Bus current sense voltage	I_{Sense}	—	563	—	mV/A
Bus voltage sense voltage	V_{Bus}	—	8.09	—	mV/V
Peak output current	I_{PK}	—	—	2.8	A
Brake resistor dissipation (continuous)	P_{BK}	—	—	50	W
Brake resistor dissipation (15 sec pk)	$P_{BK(Pk)}$	—	—	100	W
Total power dissipation	P_{diss}	—	—	85	W

4.6 Optoisolation Board

Motorola's embedded motion control series optoisolation board links signals from a controller to a high-voltage power stage. The board isolates the controller, and peripherals that may be attached to the controller, from dangerous voltages that are present on the power stage. The optoisolation board's galvanic isolation barrier also isolates control signals from high noise in the power stage and provides a noise-robust systems architecture.

Signal translation is virtually one-for-one. Gate drive signals are passed from the controller to the power stage via high-speed, high dv/dt, digital optocouplers. Analog feedback signals are passed back through HCNR201 high-linearity analog optocouplers. Delay times are typically

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250 ns for digital signals, and 2 µs for analog signals. Grounds are separated by the optocouplers' galvanic isolation barrier.

Both input and output connections are made via 40-pin ribbon cable connectors. The pin assignments for both connectors are the same. For example, signal PWM_AT appears on pin 1 of the input connector and also on pin 1 of the output connector. In addition to the usual motor control signals, an MC68HC705JJ7CDW serves as a serial link, which allows controller software to identify the power board.

Power requirements for the controller side circuitry are met with a single external 12-Vdc power supply. Power for power stage side circuitry is supplied from the power stage through the 40-pin output connector.

The electrical characteristics in **Figure 4-3** apply to operation at 25°C, and a 12-Vdc power supply voltage.

Table 4-3. Electrical Characteristics

Characteristic	Symbol	Min	Typ	Max	Units	Notes
Power Supply Voltage	Vdc	10	12	30	V	
Quiescent Current	I_{CC}	70(1)	200(2)	500(3)	mA	dc/dc converter
Min Logic 1 Input Voltage	V_{IH}	2.0	—	—	V	HCT logic
Max Logic 0 Input Voltage	V_{IL}	—	—	0.8	V	HCT logic
Analog Input Range	V_{In}	0	—	3.3	V	
Input Resistance	R_{In}	—	10	—	kΩ	
Analog Output Range	V_{Out}	0	—	3.3	V	
Digital Delay Time	t_{DDLY}	—	0.25	—	µs	
Analog Delay Time	t_{ADLY}	—	2	—	µs	

1. Power supply powers optoisolation board only.
2. Current consumption of optoisolation board plus DSP EMV board (powered from this power supply)
3. Maximum current handled by dc/dc converters

4.7 Motor-Brake Specifications

The AC induction motor-brake set incorporates a 3-phase AC induction motor and attached BLDC motor brake. The AC induction motor has four

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poles. The incremental position encoder is coupled to the motor shaft, and position Hall sensors are mounted between motor and brake. They allow sensing of the position if required by the control algorithm. Detailed motor-brake specifications are listed in **Table 4-4**.

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Table 4-4. Motor - Brake Specifications

Set Manufactured	EM Brno, Czech Republic	
Motor Specification:	eMotor Type:	AM40V 3-Phase AC Induction Motor
	Pole-Number:	4
	Nominal Speed:	1300 rpm
	Nominal Voltage:	3 x 200 V
	Nominal Current:	0.88 A
Brake Specification:	Brake Type:	SG40N 3-Phase BLDC Motor
	Nominal Voltage:	3 x 27 V
	Nominal Current:	2.6 A
	Pole-Number:	6
	Nominal Speed:	1500 rpm
Position Encoder	Type:	Baumer Electric BHK 16.05A 1024-12-5
	Pulses per Revolution:	1024

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Section 5. Software Design

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5.2 Data Flow

The requirements of the drive dictates the software gather some values from the user interface and sensors, process them and generate 3-phase PWM signals for the inverter.

The control algorithm of a closed loop AC drive is described in **Figure 5-1**. The control algorithm contains the processes described in the following subsections. The detailed description is given to the subroutines 3-phase PWM calculation and the volt per hertz control algorithm.

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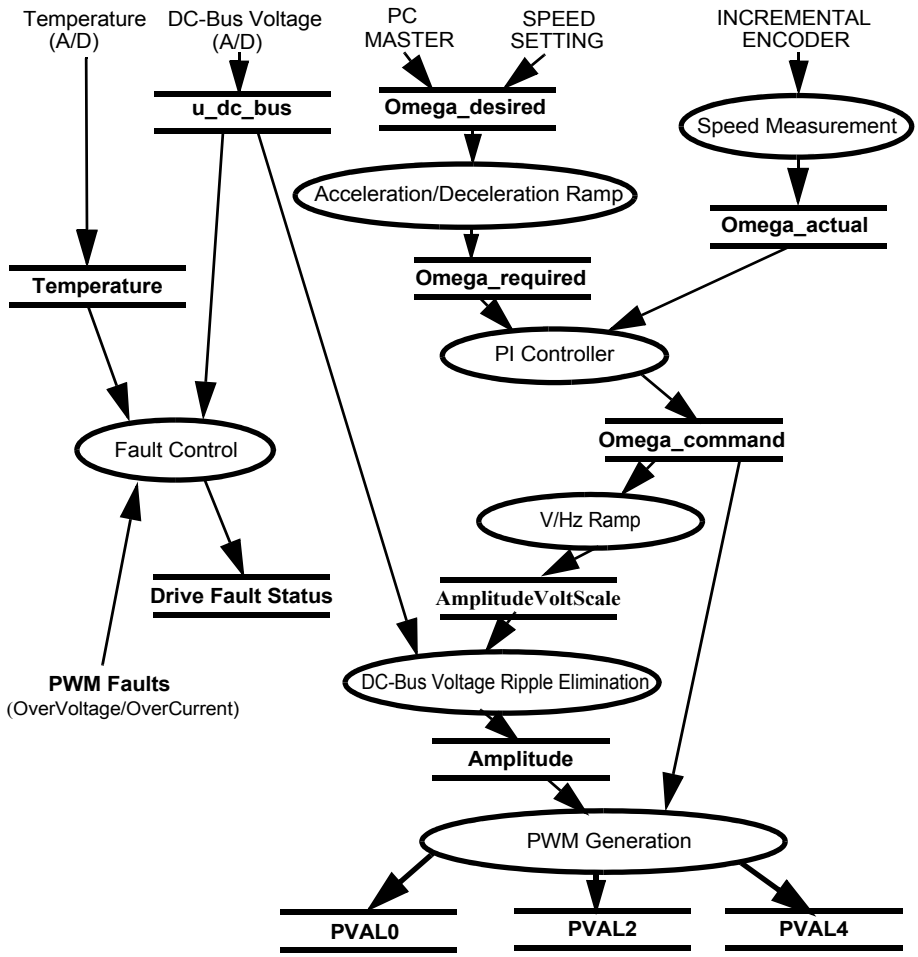

Figure 5-1. Data Flow

5.2.1 Acceleration/Deceleration Ramp

The process calculates the new actual speed command based on the required speed according to the acceleration/deceleration ramp. The desired speed is determined either by push buttons or by the PC Master.

During deceleration the motor can work as a generator. In the generator state the DC-bus capacitor is charged and its voltage can easily exceed its maximal voltage. Therefore, the voltage level in the DC-bus link is controlled by a resistive brake, operating in the case of overvoltage.

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The process input parameter is *Omega_desired,* the desired speed.

The process output parameter is *Omega_required,* used as an input parameter of the PWM generation process.

5.2.2 Speed Measurement

The speed measurement process uses the on-chip quadrature decoder. The process output is *MeasuredSpeed,* and is only used as an information value in PC Master .

5.2.3 PI Controller

The PI controller process takes the input parameters, actual speed command *Omega_required,* and actual motor speed, measured by an incremental encoder *Omega_actual.* The PI controller calculates a speed error and performs the speed PI control algorithm. The output of the PI controller is a frequency of the first harmonic sine wave to be generated by the inverter: *Omega_command*.

5.2.4 V/Hz Ramp

The drive is designed as a volt per hertz drive. It means, the control algorithm keeps the constant motor's magnetizing current (flux) by varying the stator voltage with frequency. The commonly used volt per hertz ramp of a 3-phase AC induction motor is illustrated in **Figure 5-2.**

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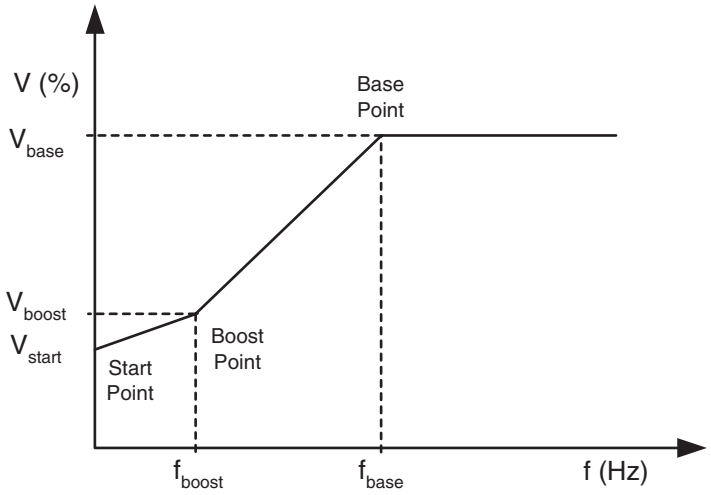

Figure 5-2. Volt per Hertz Ramp

The volt per hertz ramp is defined by the following parameters:

- Base point - defined by f_{base} (usually 50Hz or 60Hz)
- Boost point- defined by V_{boost} and f_{boost}
- Start point - defined by V_{start} at the zero frequency

The ramp profile fits to the specific motor and can be easily changed to accommodate different ones.

Process Description

The voltage ripple elimination process eliminates the influence of the DC-bus voltage ripples to the generated phase voltage sine waves. In fact, it lowers the 50 or 60Hz acoustic noise of the motor. Another positive aspect due to this function is that the generated phase voltage. is independent of the level of DC-bus voltage. So, the application is well adaptable in worldwide power supply system.

The process is performed by the *ElimDCVoltRipple* function, converting the phase voltage amplitude (*AmplitudeVoltScale*) to the sine wave amplitude (*Amplitude*) based on the actual value of the DC-bus voltage

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(*u_dc_bus*) and inverse value of the modulation index (*ModulationIndexInverse*).

The *modulation index* is the ratio between the maximum amplitude of the first harmonic of the phase voltage (in voltage scale) and half of DC bus voltage (in voltage scale) which is defined by the following formula:

$$m_i = \frac{U_{phasemax}^{(1)}}{\frac{1}{2} \cdot u_{DCBus}} = \frac{2}{\sqrt{3}} \quad \textbf{(5-1)}$$

The modulation index is specific to a given 3-phase generation algorithm and in the case of the application, it is 1.27.

NOTE: *The result of the modulation index is based on the third harmonic injection PWM technique.*

The first chart in **Figure 5-3** demonstrates how the *Amplitude* (in scale of generated sine wave amplitude) is counter-modulated in order to eliminate the DC-bus ripples. The second chart delineates the duty cycles generated by one of the 3-phase wave generation functions. The third chart contains symetrical sine-waves of the phase-to-phase voltages actually applied to the 3-phase motor.

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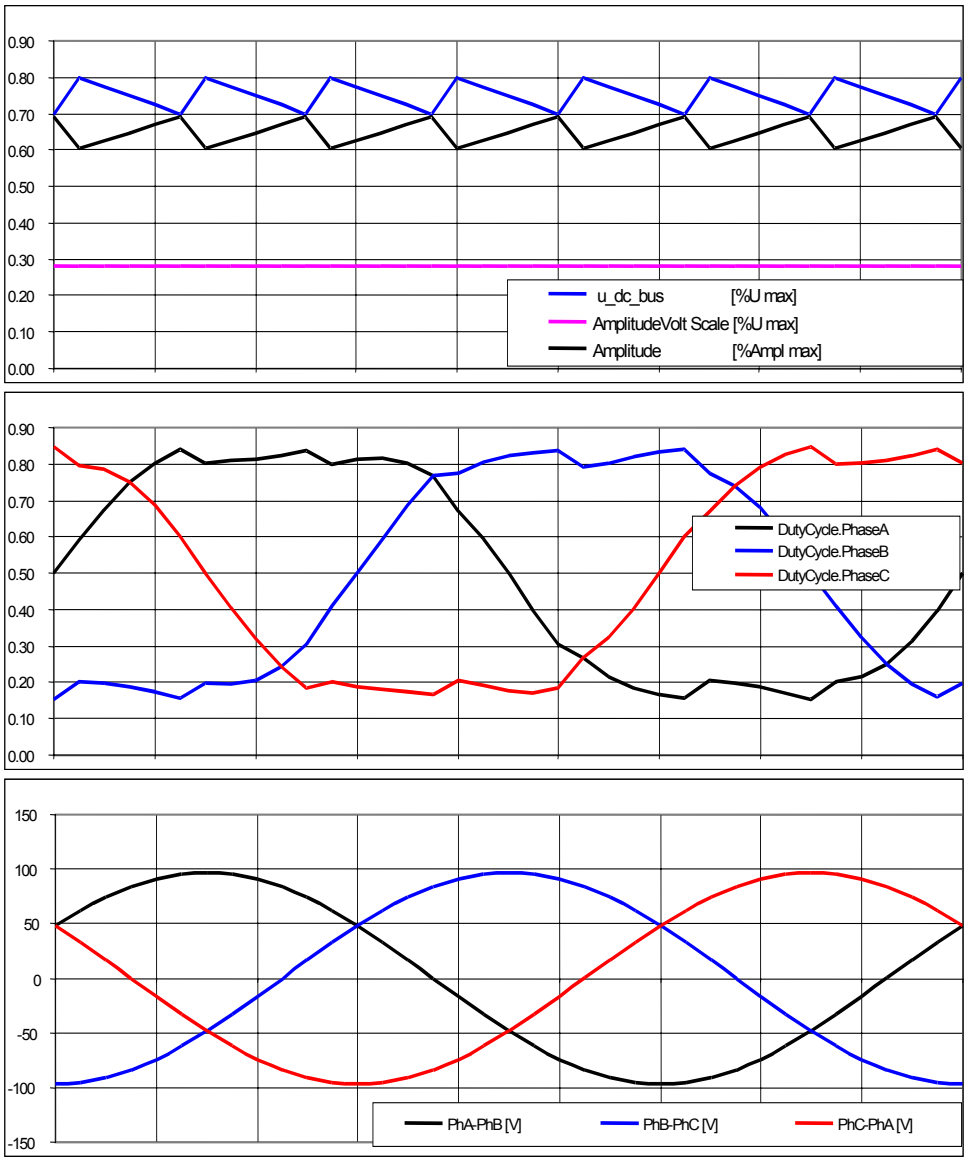

Figure 5-3. 3-ph Waveforms with DC-Bus Voltage Ripple Elimination

5.2.5 PWM Generation

Process Description

This process generates a system of 3-phase sine waves with addition of the third harmonic component shifted by 120^{o} to each other using

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Gen3PhWaveSine3rdHIntp function from the motor control function library.

The function is based on a fix wave table describing the first quadrant of sine wave stored in data memory of the DSP. Due to the symmetry of the sine function, the data in other quadrants are calculated using the data of first quadrant. It saves the data memory. The sine wave generation for the phase A, simplicity, is explained in **Figure 5-4** *The phases B and C are shifted by 120^{o} with respect to the Phase A*.

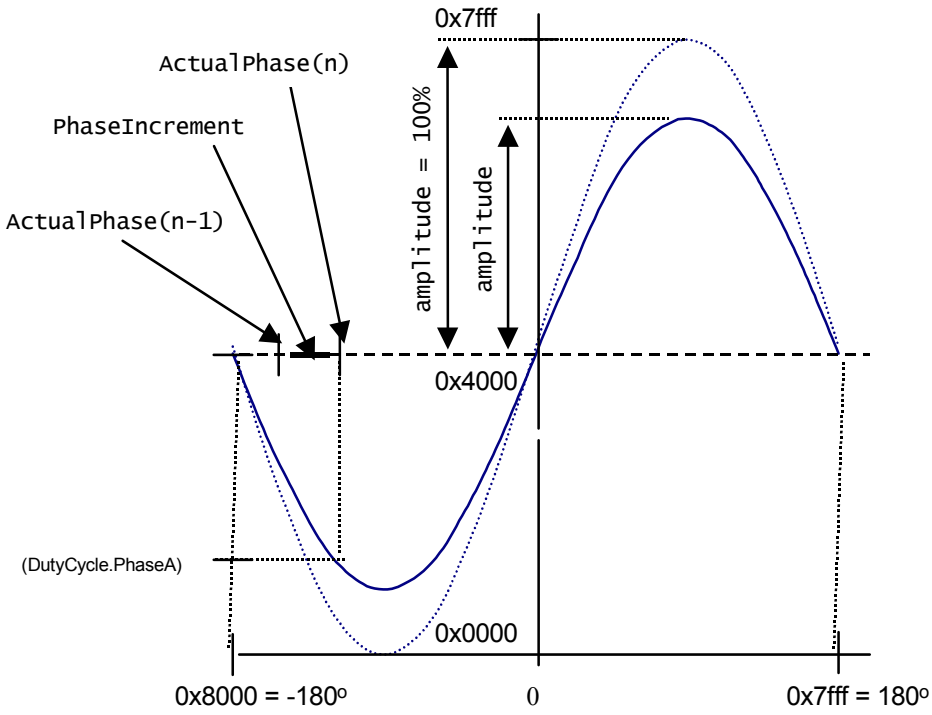

Figure 5-4. Sinewave generation

Each time the waveform generation function is called, *ActualPhase* from the previous step is updated by *PhaseIncrement*, and according to the calculated phase the value of sine is fetched from the sine table (using the function *SinPIx* from the algorithms library). Then it's multiplied by the amplitude and passed to the PWM. For the explanation of the a 3-phase waveform generation with the 3rh harmonic addition, see the following formulas.

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$$PWMA = \frac{1}{\sqrt{3}} \cdot Amplitude \cdot \left(\sin\alpha + \frac{1}{6} \cdot \sin 3\alpha\right) + 0.5$$
$$PWMB = \frac{1}{\sqrt{3}} \cdot Amplitude \cdot \left(\sin(\alpha - 120^0) + \frac{1}{6} \cdot \sin 3\alpha\right) + 0.5 \quad \textbf{(5-2)}$$
$$PWMC = \frac{1}{\sqrt{3}} \cdot Amplitude \cdot \left(\sin(\alpha - 240^0) + \frac{1}{6} \cdot \sin 3\alpha\right) + 0.5$$

Where PWMA, PWMB and PWMC are calculated, dutycycles passed to the PWM driver and the amplitude determines the level of the phase voltage amplitude.

The process that is performed in the PWM reload callback function: *isrPWM_A_Reload* is accessed regularly at the rate given by the set PWM reload frequency. This process is repeated often enough to compare it to the wave frequency. Wave length comparisons are made to generate the correct wave shape. Therefore, for the 16kHz PWM frequency, it is called each 4th PWM pulse, thus the PWM registers are updated in the 4kHz rate (each 250µsec).

Figure 5-5 shows the dutycycles generated by the *Gen3PhWaveSine3rdHIntp* function when *Amplitude* is 1 (100%).

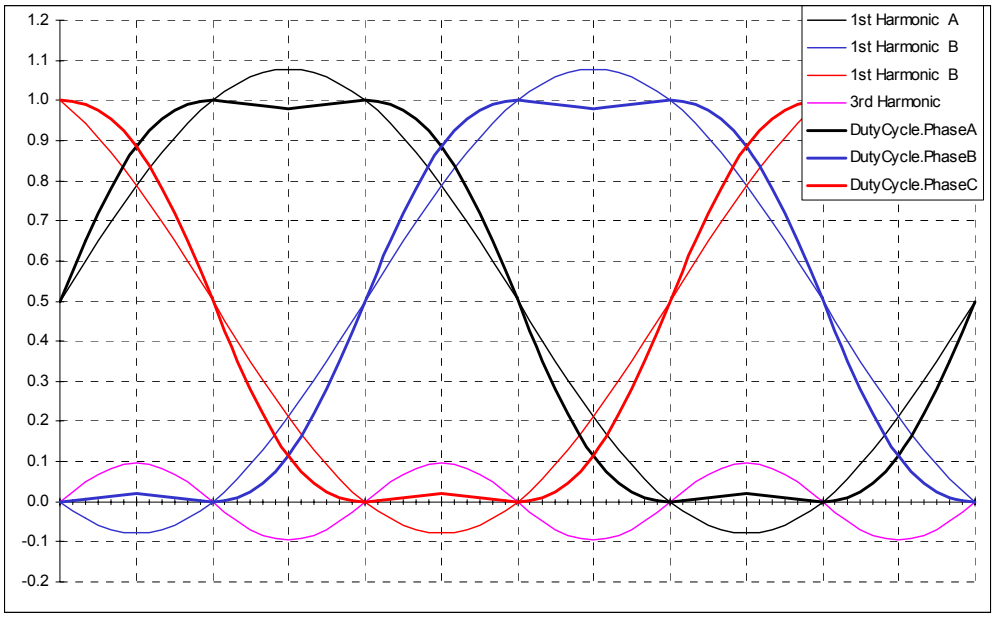

Figure 5-5. 3-ph Sine Waves with 3rd Harm. Injection, *Amp.* = 100%

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Figure 5-6 defines the dutycycles generated by the *Gen3PhWaveSine3rdHIntp* function when *Amplitude* is 0.5 (50%).

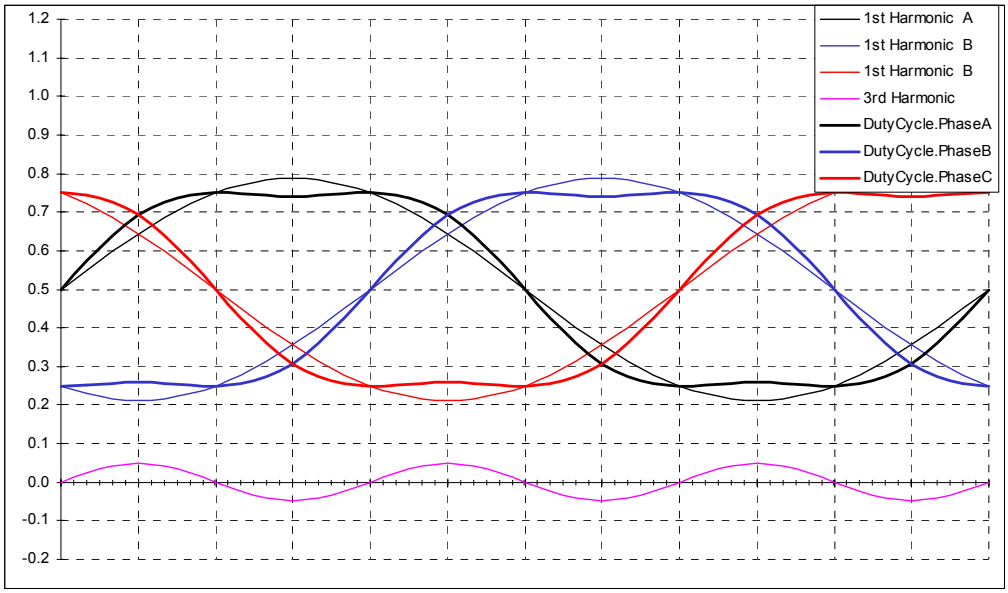

Figure 5-6. 3-ph Sine Waves with 3rd Harm. Injection, *Amp.* = 50%

Input process:

- *Amplitude* - obtained from DC-bus ripple elimination process
- *Omega_required* - obtained from acceleration/deceleration ramp process

Output process:

Results calculated by the *Gen3PhWaveSine3rdHIntp* function are directly passed to the PWM value registers using the PWM driver.

5.2.6 Fault Control

This process is responsible for the fault handling. The software accommodates five fault inputs: the overcurrent, the overvoltage, the undervoltage, the overheating and the wrong identified hardware.

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Overcurrent: In the case of the overcurrent in DC-Bus link, the external hardware provides a rising edge on the fault input pin FAULTA1 of the DSP. This signal immediately disables all the motor control PWM's outputs (PWM1 - PWM6) and sets the *DC_Bus_OverCurrent* bit of *DriveFaultStatus* variable.

Overvoltage: In the case of the overvoltage in DC-bus link, the external hardware provides a rising edge on the fault input pin FAULTA0 of the DSP. This signal immediately disables all motor control PWM's outputs (PWM1 - PWM6) and sets the *DC_Bus_OverVoltage* bit of the *DriveFaultStatus* variable.

Undervoltage: The DC-bus voltage sensed by the ADC is compared with the limit within the software. In the case of the undervoltage after a period defined by UNDERVOLTAGE_COUNT all the motor control PWM outputs are disabled and the *DriveFaultStatus* variable is set to *DC_Bus_UnderVoltage.*

Overheating: The temperature of the power module sensed by the ADC is compared with the limit within the software. In the case of the overheating after a period defined by OVERHEATING_COUNT all the motor control PWM outputs are disabled and the *DriveFaultStatus* variable is set to *OverHeating.*

Wrong Hardware: In the case the wrong hardware is identified (a different power module or missing an optoisolation board) during initialization, the *DriveFaultStatus* variable is set to *Wrong_Hardware.*

If any of the above mentioned faults occurs, program run into infinite loop and waits for reset. Fault is signalled by user LEDs on the controller board and on the PC Master control screen.

5.3 State Diagram

The general state diagram incorporates the main routine entered from reset, and the interrupt states. The main routine includes the initialization of the DSP and the main loop. The main loop incorporates the initialization state, the application state machine and the check run/stop switch state.

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The interrupt states provides calculation of the actual speed of motor, the PWM reload interrupt, the ADC service, the limit analog values handling, the overcurrent and the overvoltage PWM fault handler, and so on.

5.3.1 Initialization

The main routine provides the initialization of the DSP:

- Initializes the PLL clock
- COP and LVI are disabled
- Identifies the connected hardware
- Initializes the analog-to-digital converter
- Initializes the timers for the speed ramp and the LED handler
- Initializes the PWM module:
  - Center aligned complementary PWM mode, positive polarity
  - Sets callback for the PWM reload to (every 4th. PWM pulse)
  - Sets callback for the PWM faults
  - Sets the PWM modulus - (defines the PWM frequency)
  - enables the fault interrupts
- Sets-up I/O ports (push buttons, switch, brake)
- Initializes the quadrature decoder for the speed measurement
- Initializes algorithms (V/Hz look-up table, sinewave generator)
- Enables interrupts

The board identification routine identifies the connected power stage board by decoding the identified message sent from the power stage. If the wrong power stage is identified, the program goes to the infinite loop, displaying the fault status on the LED. The state can be left only by the RESET.

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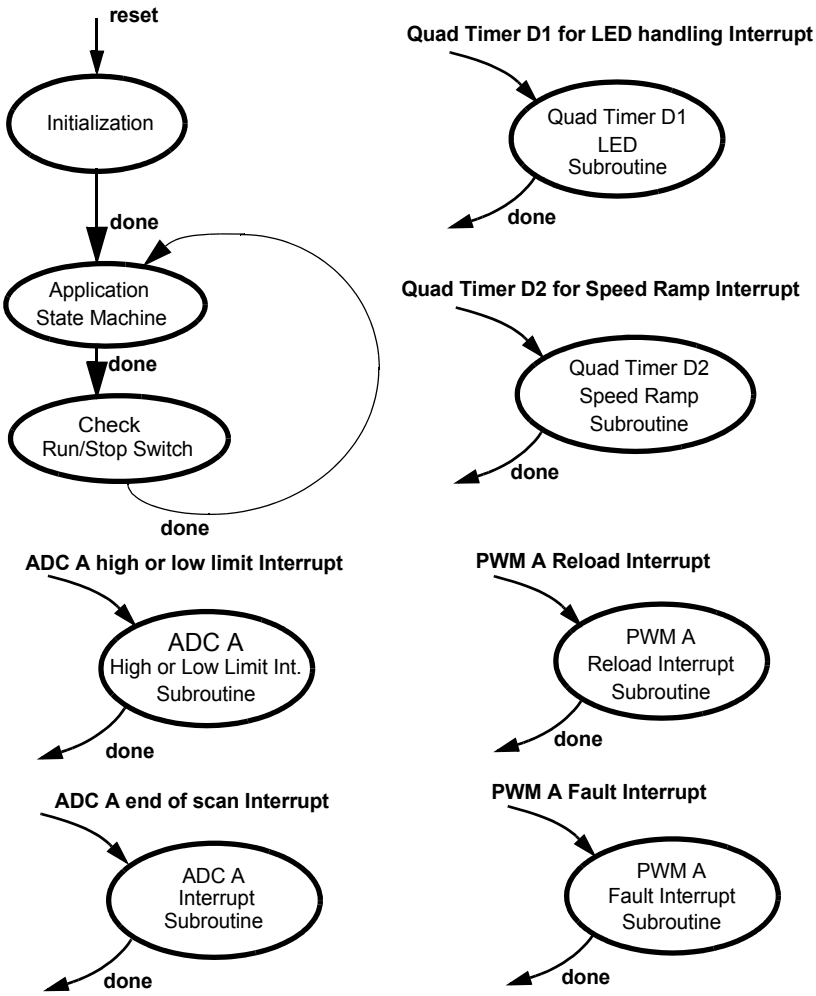

Figure 5-7. State Diagram - General Overview

5.3.2 Application State Machine

This state controls the main application functionalities, depicted in **Figure 5-8**.

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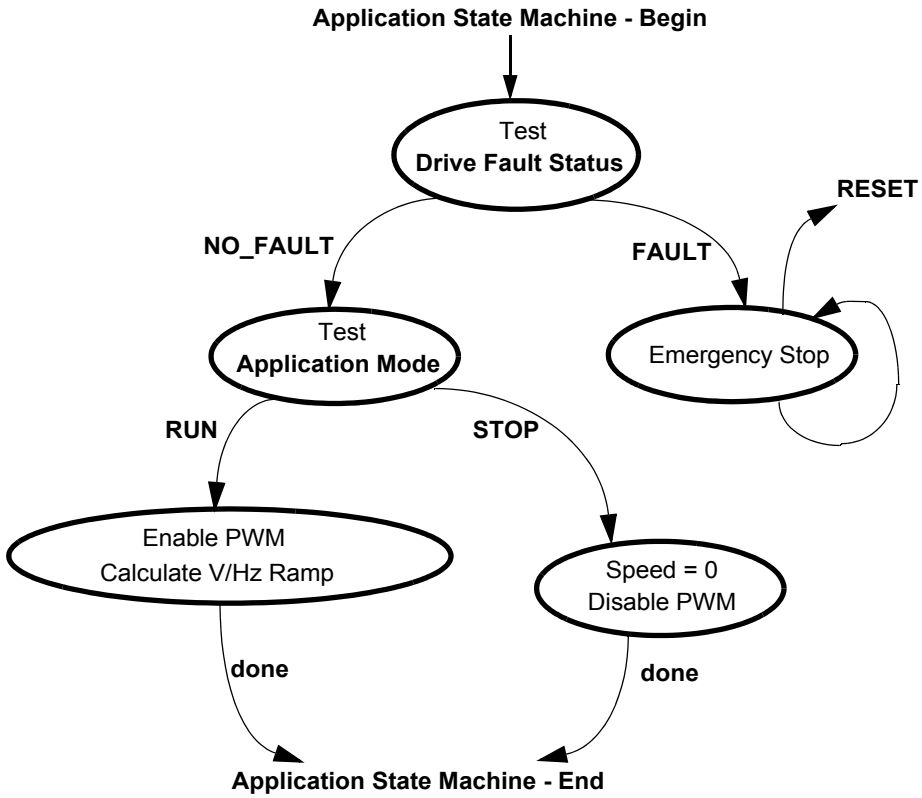

Figure 5-8. State - Application State Machine

5.3.3 Check Run/Stop Switch

In this state, the Run/Stop switch is checked according to the Application Mode setting; whether set to RUN or STOP.

5.3.4 PWM A Reload ISR

This subroutine is called at the PWM A reload interrupt. It provides:

- The measurement of the actual speed (*MeasuredSpeed*)
- The elimination of DC-bus voltage ripples (*ElimDCBVoltRipple* function)
- The calculation of the waveform generator (*Gen3PhWaveSine3rdHIntp* function)

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- The update of PWM value registers
- The Start of the ADC conversion

The name of the callback function in the code: *void* ***isrPWM_A_Reload****(void).*

5.3.5 PWM A Fault ISR

This disables the PWM module and sets *DriveFaultStatus* |= *DC_Bus_OverVoltage* or *DC_Bus_OverCurrent* according to the fault input pin level in the case of the overvoltage or the overcurrent in the DC-Bus line.

The name of the callback function in the code: *void* ***isrPWM_A_Fault****(void).*

This subroutine is called at the PWM A Fault Interrupt.

5.3.6 ADC End Of Scan ISR

The following analog inputs are read:

- DC-Bus Voltage
- DC-Bus Current
- Temperature of the Power Stage Module

Also the detection of faults caused by the overheating and the undervoltage is performed in this subroutine.

The name of the callback function in the code: void ***isrADC_A_EndOfScan****(void).*

This subroutine is called at the ADC conversion completion.

5.3.7 ADC High And Low Limit ISR's

This subroutine turns on and off the resistive brake in the DC-Bus link. When the actual voltage of DC-Bus *u_dc_bus* is higher than

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BRAKE_HIGH_LIMIT the brake is turned on. When the actual voltage of DC-Bus *u_dc_bus* is lower than *BRAKE_LOW_LIMIT* the brake is turned off.

The Name of the callback function in the code: *void* ***isrADC_A_Limit****(void)*.

5.3.8 Quad Timer D1 Compare ISR

This subroutine takes care of the LED handling.

The name of the callback function in the code: *void* ***isrQT_D1****(void)*.

Access frequency is defined by constant *TMR_1_PERIOD* in definition section of program.

5.3.9 Quad Timer D2 ISR

This subroutine takes care of Speed ramp calculation.

Name of callback function in code: *void* ***isrQT_D2****(void)*.

Access frequency is defined by constant *TMR_2_PERIOD* in the definition section of the program.

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Section 6. Application Setup

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6.2 Application Description

This application performs a principal control of the 3-phase AC Induction motor using the DSP56F805 processor. The control technique sets the speed ([rpm], [Hz]) of the magnetic field and calculates the phase voltage amplitude according to a V/Hz table. This table is private to the application and reflects AC induction motor parameters (Base Voltage/frequency; Boost Voltage/frequency; DC Boost Voltage).The incremental encoder is used to derive the actual rotor speed.

The closed loop system is characterized by a feedback signal (Actual speed), derived from a quadrature decoder in the controlled system. This signal monitors the actual behavior of the system, and is compared with the reference signal (Required Speed). The magnitude and polarity of the resulting error signal are directly related to the difference between required and actual values of the controlled variable, which may be the speed of a motor. The error signal is amplified by the controller, and the controller output makes a correction to the controlled system, reducing the error signal.

Overcurrent, Overvoltage, Undervoltage, and Overheating protections are provided.

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Application Setup

The Volt per Hertz control algorithm is calculated on the Motorola DSP56F805. The algorithm generates the 3-phase PWM signals for AC induction motor inverter according to the user-required inputs, measured and calculated signals.

The concept of the ACIM drive incorporates the following hardware components:

- AC induction motor--brake set
- 3-phase AC/BLDC high voltage power stage
- DSP56F805EVM boards
- Optoisolation box which is connected between the Power stage board and the DSP56F805EVM

The AC induction motor--brake set incorporates a 3-phase AC induction motor and attached BLDC motor brake. The AC induction motor has four poles. The incremental position sensor (encoder) is coupled on the motor shaft. The detailed motor--brake specifications are listed in **Table 6-1**.

This 3-Phase AC Induction Motor V/Hz Control Application can operate in two modes:

1. Manual Operating Mode
   The drive is controlled by the RUN/STOP switch (S6). The motor speed is set by the UP (S2-IRQB) and DOWN (S1-IRQA) push buttons; see **Figure 6-1** If the application runs and motor spinning is disabled (i.e., the system is ready) the USER LED (LED3, shown in **Figure 6-2**) will blink. When motor spinning is enabled, the USER LED is *On*. Refer to **Table 6-2** for application states.

Table 6-1. Motor--Brake Specifications

Set Manufactured	EM Brno, Czech Republic

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Table 6-1. Motor--Brake Specifications

Motor Specification	**Motor Type**	AM40V 3-Phase AC Induction Motor
	Pole-Number	4
	Nominal Speed	1300 rpm
	Nominal Voltage	3 x 200V
	Nominal Current:	0.88A
Brake Specification	**Brake Type**	**SG40N 3-Phase BLDC Motor**
	Pole-Number	6
	Nominal Speed	1500rpm
	Nominal Voltage	3 x 27V
	Nominal Current	2.6 A
Position Sensor (Encoder)	**Type**	**Baumer Electric BHK 16.05A 1024-12-5**
	Pulses per revolution	1024

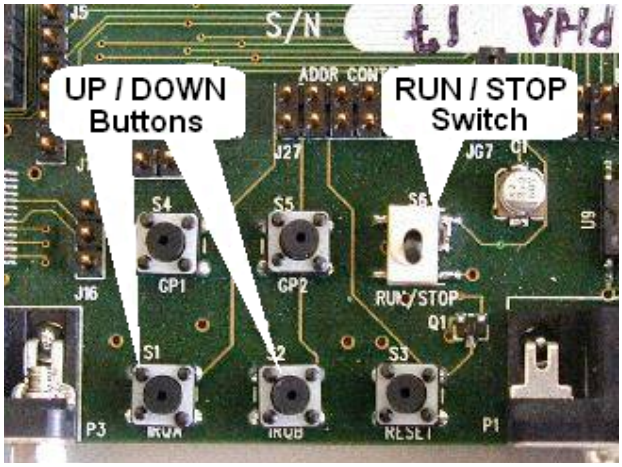

Figure 6-1. RUN/STOP Switch and UP/DOWN Buttons

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Application Setup

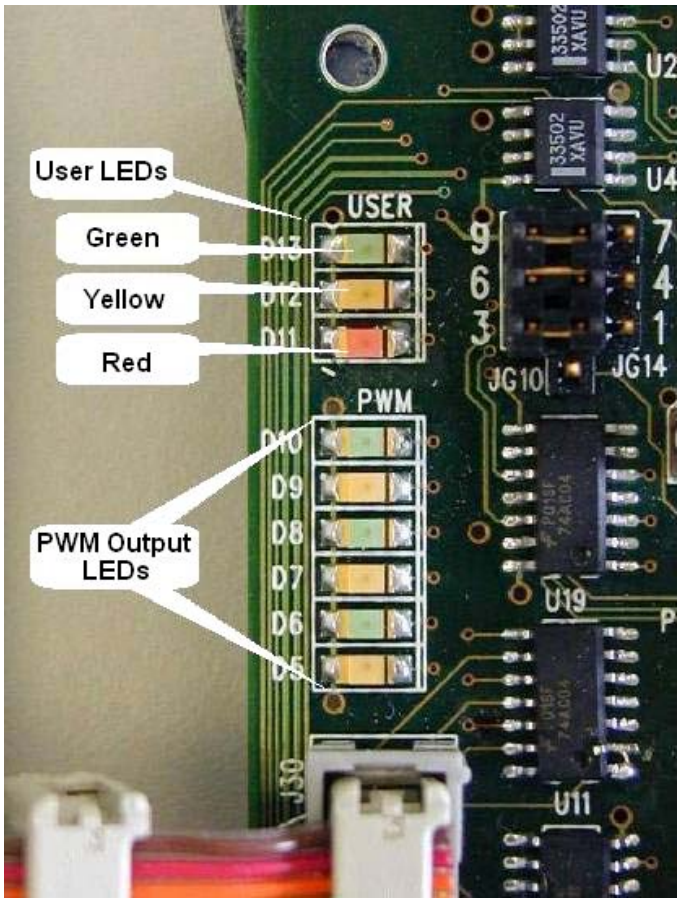

Figure 6-2. USER and PWM LEDs at DSP56F805EVM

Table 6-2. Motor Application States

Application State	Motor State	Green LED State
Stopped	Stopped	Blinking at a frequency of 2Hz, red led status is off
Running	Spinning	On, red led status is off
Fault	Stopped	Blinking at a frequency of 8Hz, red led status is on

2. PC master software (Remote) Operating Mode
   The drive is controlled remotely from a PC through the SCI

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communication channel of the DSP device via an RS-232 physical interface. The drive is enabled by the RUN/STOP switch, which can be used to safely stop the application at any time. PC master software enables to set the required speed of the motor.

PC master software displays the following information:

- Applied Voltage
- Required Voltage
- Speed
- RUN/STOP Switch Status
- Application Mode

Measured quantities include:

- DCBus voltage
- Power module temperature
- Rotor speed

The faults used for drive protection:

- Overvoltage (PC master software error message = *Overvoltage fault*)
- Undervoltage (PC master software error message = *Undervoltage fault*)
- Overcurrent (PC master software error message = *Overcurrent fault*)
- Overheating (PC master software error message = *Overheating fault*)
- Wrong-hardware (PC master software error message = *Wrong HW used*)

Start the PC master software window's application, *3acim_vhz.pmp.* **Figure 6-3** illustrates the PC master software control window after this project has been launched.

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NOTE: If the PC master software project (*.pmp* file) is unable to control the application, it is possible that the wrong load map (*.elf* file) has been selected. PC master software uses the load map to determine addresses for global variables being monitored. Once the PC master software project has been launched, this option may be selected in the PC master software window under *Project/Select Other Map FileReload*.

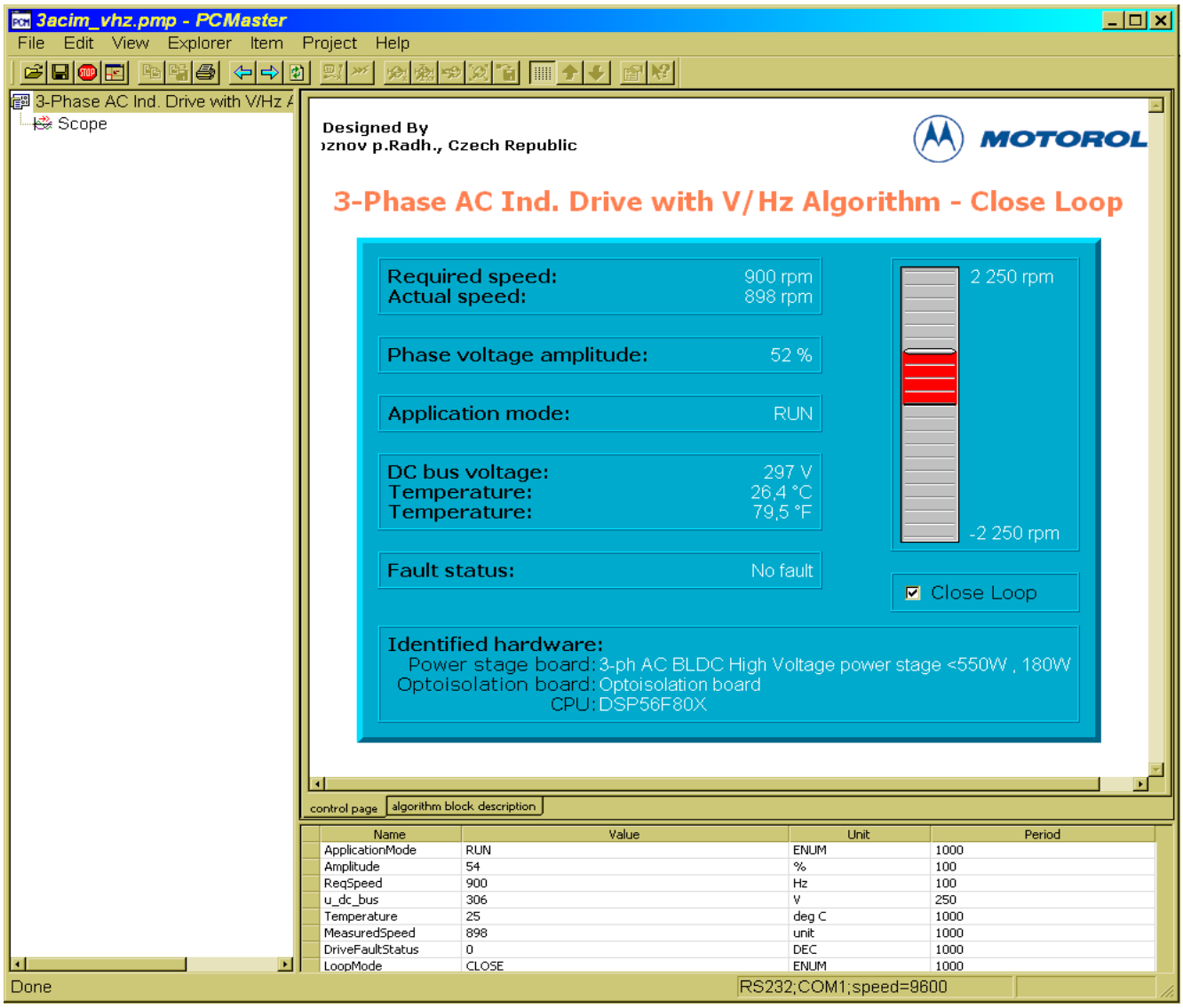

Figure 6-3. PC Master Software Control Window

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6.3 Application Setup

Figure 6-4 illustrates the hardware set-up for the AC Induction Motor V/Hz Control Application.

The system consists of the following components:

- AC Induction motor Type AM40V, EM Brno s.r.o., Czech Republic
- Load Type SG 40N, EM Brno s.r.o., Czech Republic
- Encoder BHK 16.05A1024-12-5, Baumer Electric, Switzerland
- 3-ph. AC BLDC HV Power Stage 180 W
- Optoisolation Board
- DSP56F805 Board:
  - DSP56F805 Evaluation Module, supplied as DSP56F805EVM
  - or DSP56F805 Controller Board
- The serial cable - needed for the PC master software debugging tool only.
- The parallel cable - needed for the Metrowerks Code Warrior debugging and s/w loading.

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Application Setup

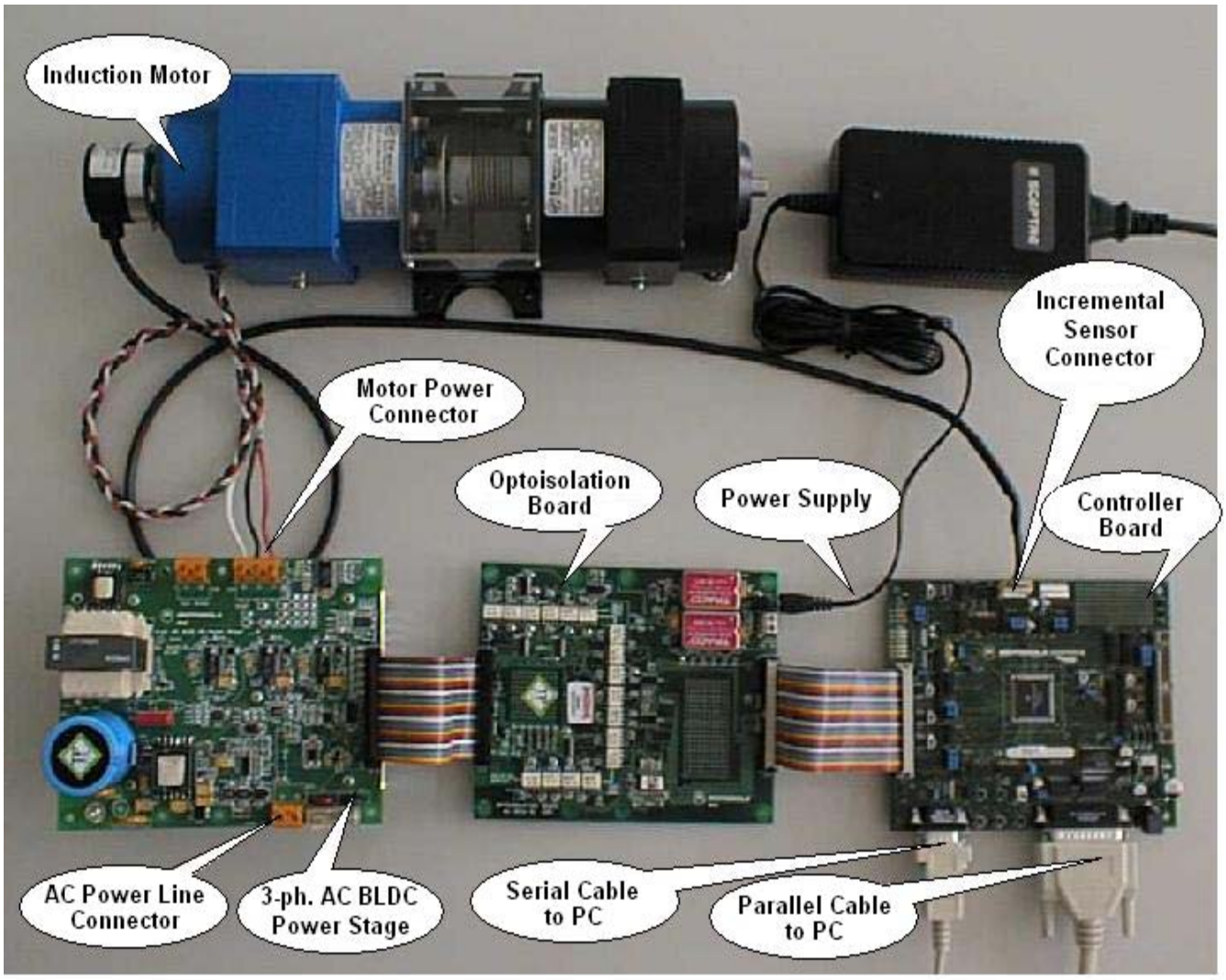

Figure 6-4. Set-up of the 3-Phase ACIM V/Hz Control Application

6.3.1 Application Set-Up Using DSP56F805EVM

To execute the AC Induction Motor V/Hz Control, the DSP56F805EVM board requires the strap settings shown in **Figure 6-5** and **Table 6-3**.

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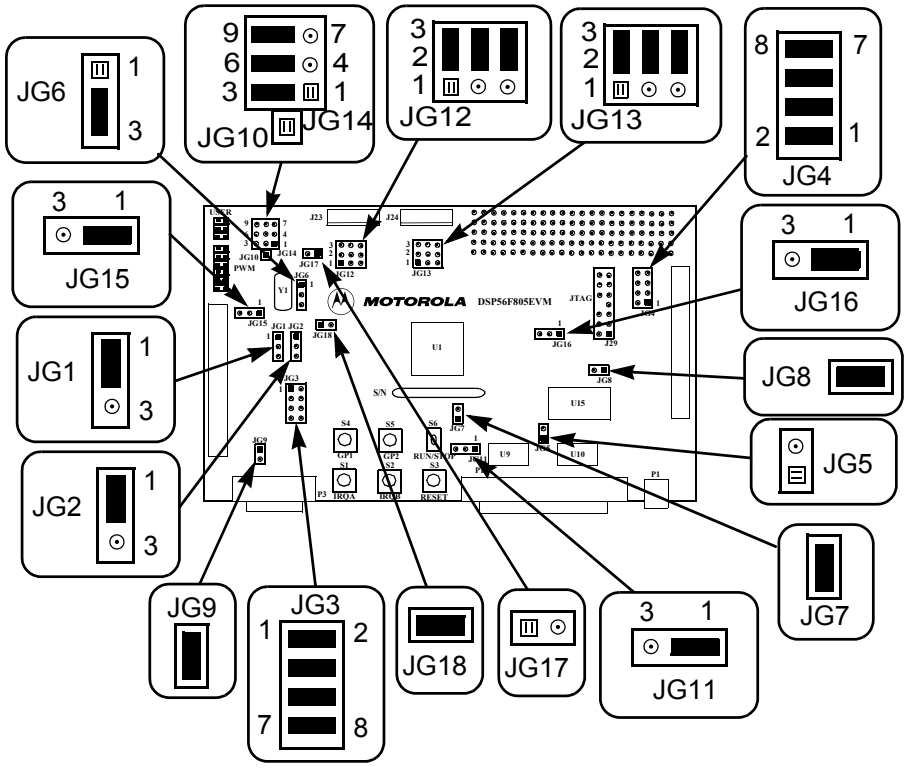

Figure 6-5. DSP56F805EVM Jumper Reference

Table 6-3. DSP56F805EVM Jumper Settings

Jumper Group	Comment	Connections
JG1	PD0 input selected as a high	1-2
JG2	PD1 input selected as a high	1-2
JG3	Primary UNI-3 serial selected	1-2, 3-4, 5-6, 7-8
JG4	Secondary UNI-3 serial selected	1-2, 3-4, 5-6, 7-8
JG5	Enable on-board parallel JTAG Command Converter Interface	NC
JG6	Use on-board crystal for DSP oscillator input	2-3
JG7	Select DSP's Mode 0 operation upon exit from reset	1-2
JG8	Enable on-board SRAM	1-2
JG9	Enable RS-232 output	1-2

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Table 6-3. DSP56F805EVM Jumper Settings

Jumper Group	Comment	Connections
JG10	Secondary UNI-3 Analog temperature input unused	NC
JG11	Use Host power for Host target interface	1-2
JG12	Primary Encoder input selected for quadrature encoder signals	2-3, 5-6, 8-9
JG13	Secondary Encoder input selected	2-3, 5-6, 8-9
JG14	Primary UNI-3 3-Phase Current Sense selected as Analog Inputs	2-3, 5-6, 8-9
JG15	Secondary UNI-3 Phase A Overcurrent selected for FAULTA1	1-2
JG16	Secondary UNI-3 Phase B Overcurrent selected for FAULTB1	1-2
JG17	CAN termination unselected	NC
JG18	Use on-board crystal for DSP oscillator input	1-2

When running the EVM target system in a stand-alone mode from Flash, the JG5 jumper must be set in the 1-2 configuration to disable the command converter parallel port interface.

6.4 Project Files

The 3-Phase AC Induction Motor V/Hz Control application is composed of the following files:

- **...\3acim_vhz_sa\3acim_vhz.c,** main program
- **...\3acim_vhz_sa\3acim_vhz_sa.mcp,** application project file
- **...\3acim_vhz_sa\ApplicationConfig\appconfig.h,** application configuration file
- **...\3acim_vhz_sa\SystemConfig\ExtRam\linker_ram.cmd,** linker command file for external RAM
- **...\3acim_vhz_sa\SystemConfig\Flash\linker_flash.cmd,** linker command file for Flash
- **...\3acim_vhz_sa\SystemConfig\Flash\flash.cfg,** configuration file for Flash

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- **...\3acim_vhz_sa\PCMaster\3acim_vhz.pmp**, PC Master software file

These files are located in the application folder.

Motor Control algorithms used in the application:

- **...\controller.c, .h**: source and header files for PI controller
- **...\ramp.c, .h**: source and header files for ramp controller
- **...\sinquad.c, .h**: source and header files with the sine look-up table
- **...\trigon.c, .h**: source and header files for sine calculation funcion
- **...\mcgen.c, .h**: source and header files for three-phase sine wave generation
- **...\lut.c, .h**: source and header files for look-up table algorithm
- **...\ripelim.c, .h**: source and header files for DC bus voltage ripple elimination algorithm

Other functions used in the application:

- **...\boardId.c, .h**: source and header files for the board identification function

This application runs stand-alone, i.e. all the needed files are concentrated in one project folder. Quick_Start libraries are:

- **...\3acim_vhz_sa\src\include**, folder for general C-header files
- **...\3acim_vhz_sa\src\dsp56805**, folder for the device specific source files, e.g. drivers
- **...\3acim_vhz_sa\src\pc_master_support**, folder for PC master software source files
- **...\3acim_vhz_sa\src\algorithms**, folder for algorithms

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6.5 Application Build & Execute

When building the 3-Phase AC Induction V/Hz Control Application, the user can create an application that runs from internal *Flash* or *External RAM*. To select the type of application to build, open the *3acim_vhz_sa.mcp* project and select the target build type, as shown in **Figure 6-6** A definition of the projects associated with these target build types may be viewed under the *Targets* tab of the project window.

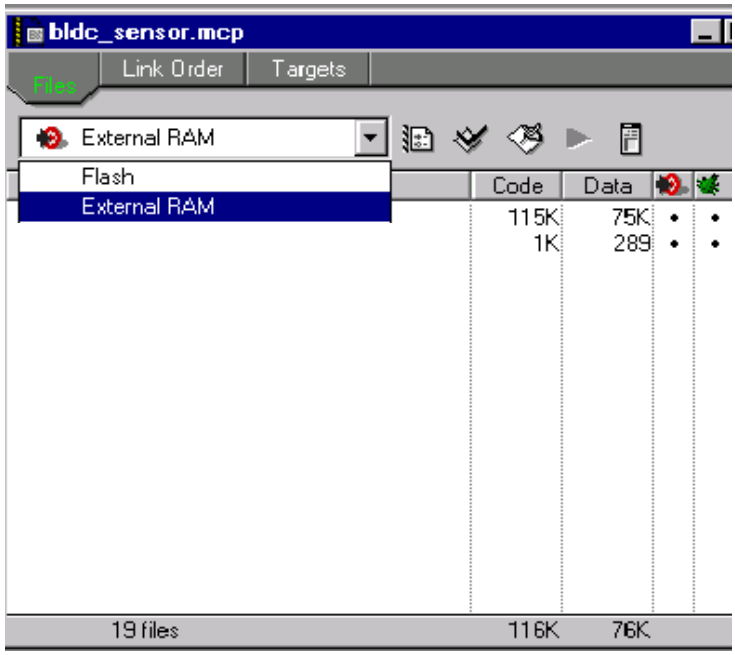

Figure 6-6. Target Build Selection

The project may now be built by executing the *Make* command, as shown in **Figure 6-7** This will build and link the 3-Phase AC Induction Motor V/Hz Control Application and all needed Metrowerks.

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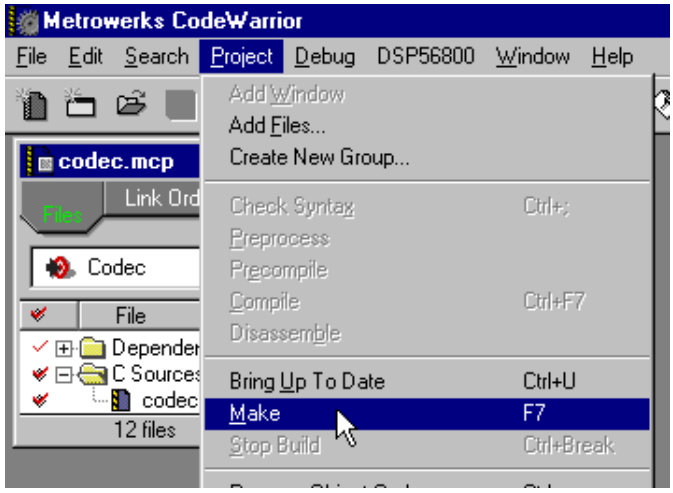

Figure 6-7. Execute *Make* Command

To execute the 3-Phase AC Induction Motor V/Hz Control application, select *Project\Debug* in the CodeWarrior IDE, followed by the *Run* command. For more help with these commands, refer to the CodeWarrior tutorial documentation in the following file located in the CodeWarrior installation folder:

<...>\CodeWarrior Documentation\PDF\Targeting_DSP56800.pdf

If the Flash target is selected, CodeWarrior will automatically program the internal Flash of the DSP with the executable generated during *Build*. If the External RAM target is selected, the executable will be loaded to off-chip RAM.

Once Flash has been programmed with the executable, the EVM target system may be run in a stand-alone mode from Flash. To do this, set the JG5 jumper in the 1-2 configuration to disable the parallel port, and press the RESET button.

Once the application is running, move the RUN/STOP switch to the RUN position and set the required speed using the UP/DOWN push buttons. Pressing the UP/DOWN buttons should incrementally increase the motor speed until it reaches maximum speed. If successful, the induction motor will be spinning.

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Application Setup

NOTE: *If the RUN/STOP switch is set to the RUN position when the application starts, toggle the RUN/STOP switch between the STOP and RUN positions to enable motor spinning. This is a protection feature that prevents the motor from starting when the application is executed from CodeWarrior.*

You should also see a lighted green LED, which indicates that the application is running. If the application is stopped, the green LED will blink at a 2Hz frequency. If any fault occurs, the green LED will blink at a frequency of 8Hz.

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Appendix A. References

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Appendix B. Glossary

AC — Alternating Current.

ADC — See “analogue-to-digital converter”.

brush — A component transfering elektrical power from non-rotational terminals, mounted on the stator, to the rotor

BLDC — Brushless dc motor.

commutation — A process providing the creation of a rotation field by switching of power transistor (electronic replacement of brush and commutator)

commutator — A mechanical device alternating DC current in DC commutator motor and providing rotation of DC commutator motor

COP — Computer Operating Properly timer

DC — Direct Current.

DSP — Digital Signal Prosessor.

DSP56F80x — A Motorola family of 16-bit DSPs dedicated for motor control.

DT — see “Dead Time (DT)”

Dead Time (DT) — short time that must be inserted between the turning off of one transistor in the inverter half bridge and turning on of the complementary transistor due to the limited switching speed of the transistors.

duty cycle — A ratio of the amount of time the signal is on versus the time it is off. Duty cycle is usually represented by a percentage.

GPIO — General Purpose Input/Output.

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Glossary

Hall Sensors - A position sensor giving six defined events (each 60 electrical degrees) per electrical revolution (for 3-phase motor)

HV — High Voltage (115 V AC or 230 V AC)

interrupt — A temporary break in the sequential execution of a program to respond to signals from peripheral devices by executing a subroutine.

input/output (I/O) — Input/output interfaces between a computer system and the external world. A CPU reads an input to sense the level of an external signal and writes to an output to change the level on an external signal.

JTAG — Interface allowing On-Chip Emulation and Programming.

LED — Light Emitting Diode

logic 1 — A voltage level approximately equal to the input power voltage (V_{DD}).

logic 0 — A voltage level approximately equal to the ground voltage (V_{SS}).

LV — Low Voltage (12 V DC)

PI controller — Proportional-Integral controller.

phase-locked loop (PLL) — A clock generator circuit in which a voltage controlled oscillator produces an oscillation which is synchronized to a reference signal.

PM — Permanent Magnet

PMSM - Permanent Magnet Synchronous Motor.

PWM — Pulse Width Modulation.

Quadrature Decoder — A module providing decoding of position from a quadrature encoder mounted on a motor shaft.

Quad Timer — A module with four 16-bit timers.

reset — To force a device to a known condition.

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RPM — Revolutions per minute.

SCI — See "serial communication interface module (SCI)."

serial communications interface module (SCI) — A module that supports asynchronous communication.

serial peripheral interface module (SPI) — A module that supports synchronous communication.

software — Instructions and data that control the operation of a microcontroller.

software interrupt (SWI) — An instruction that causes an interrupt and its associated vector fetch.

SPI — See "serial peripheral interface module (SPI)."

timer — A module used to relate events in a system to a point in time.

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